

Fast radio bursts: the observational case for a Galactic origin

Dan Maoz¹, Abraham Loeb^{1,2}, Yossi Shvartzvald^{1,3}, Monika Sitek⁴,
Michael Engel¹, Flavien Kiefer¹, Marcin Kiraga⁴, Amir Levi¹, Tsevi Mazeh¹,
Michał Pawlak⁴, R. Michael Rich⁵, Lev Tal-Or¹, Lukasz Wyrzykowski⁴

¹*School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*

²*Institute for Theory and Computation, Harvard University, Cambridge, MA 03210, USA*

³*NASA Postdoctoral Program Fellow, Jet Propulsion Laboratory, Pasadena, CA 91109, USA*

⁴*Warsaw University Observatory, 00478 Warsaw, Poland*

⁵*Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*

9 September 2015

ABSTRACT

There are by now ten published detections of fast radio bursts (FRBs)—single bright GHz-band millisecond pulses of unknown origin. Proposed explanations cover a broad range from exotic processes at cosmological distances to atmospheric and terrestrial sources. Loeb, Maoz, and Shvartzvald have previously suggested that FRB sources could be nearby flare stars, and pointed out the presence of a W-UMa-type contact binary within the beam of one out of three FRB fields that they examined. To further test the flare-star hypothesis, we use time-domain optical photometry and spectroscopy, and now find possible flare stars in additional FRB fields, with one to three such cases among all eight FRB fields studied. We evaluate the chance probabilities of these possible associations to be in the range $\sim 0.1\%$ to 9% , depending on the input assumptions. Further, we re-analyze the probability that two FRBs recently discovered 3 years apart within the same radio beam are unrelated. Contrary to other claims, we conclude with 99% confidence that the two events are from the same repeating source. The different dispersion measures between the two bursts then rule out a cosmological intergalactic-medium origin for the dispersion measure, but are consistent with the flare-star scenario with a varying plasma blanket between bursts. Finally, we review some theoretical objections that have been raised against a local flare-star FRB origin, and show that they are incorrect.

Key words: stars: radio continuum, binaries, coronae, flare stars, variables

1 INTRODUCTION

Nearly a decade after their discovery by Lorimer et al. (2007), the source and nature of fast radio bursts (FRBs) is yet unknown. FRBs are bright ($\sim 0.1 - 1$ Jy) and brief (~ 1 ms) pulses of ~ 1 GHz radio emission. The latest estimate of the rate of FRBs with flux > 0.1 Jy is $3.3^{+2}_{-1} \times 10^3 \text{ day}^{-1}$ over the whole sky (Rane et al. 2015). To date, ten candidate bursts have been reported (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Petroff et al. 2015a; Ravi et al. 2015). Nine of them have been discovered with the Parkes Radio Telescope, and one with the Arecibo Radio

Telescope. Eight of the FRBs were found in the analysis of archival data, long after the events. Two FRBs were discovered in real time (within 10 s) (Ravi et al. 2015; Petroff et al. 2015a), one of them while observing the Carina dwarf galaxy, the other while re-monitoring the location of a previous burst (FRB110220, Thornton et al. (2013)). The latter was also the first FRB with a polarization measurement, and was found to be up to $\sim 50\%$ circularly polarised, depending on the temporal part of the pulse considered. In no cases have there been known transient or eruptive counterparts at other wavelengths coincident with the FRB, including in the real-time detection by Petroff et al. (2015a), where prompt followup observations at other bands were undertaken (within

9 hrs in X-rays and within 17 hrs in the optical and near infrared). No clear consensus has emerged on whether FRBs are isotropically distributed, or avoid the Galactic plane, due to some combination of backgrounds, selection effects, and propagation effects (see, e.g. Petroff et al. 2015a; Rane et al. 2015; Macquart & Johnston 2015). An intrinsic avoidance of the Galactic plane is not expected in any model that has been proposed for FRBs.

The dispersion measures (DMs) of FRBs, i.e. the line-of-sight column densities of free electrons, as deduced from the normalisation of the f^{-2} frequency dependence of the pulse arrival times, exceed the values expected from models of the Milky Way interstellar electron distribution. FRBs have DMs in the range $\sim 300 - 1600$ pc cm $^{-3}$, or electron column densities $N_e \sim (1 - 5) \times 10^{21}$ cm $^{-2}$. FRBs have therefore been inferred to originate from extragalactic sources at cosmological distances. The intergalactic medium, perhaps combined with the DM of the sources' host galaxies, would account for the excess DM values. In one case, however (FRB010621, Keane et al. (2012)), direct estimates of the ionized gas column density in this direction show that the Galactic models underestimate the DM, placing the FRB source within the Galaxy at a distance of 8-20 kpc (Bannister & Madsen 2014), or possibly much closer if some of the DM is intrinsic to the source. In addition to the excess DM, three or four of the FRBs (Lorimer et al. (2007), one from Thornton et al. (2013), Ravi et al. (2015), and possibly Burke-Spolaor & Bannister (2014)) show frequency-dependent pulse smearing, indicative of scattering by an inhomogeneous electron distribution along the line of sight, at a level much larger than expected by the Galactic interstellar medium. The intergalactic medium has been invoked to explain this scattering as well (e.g. Macquart & Koay (2013)), but Katz (2014, 2015) has argued that the implied densities are too high and the scattering instead likely occurs near the source.

If FRB sources are extragalactic, their bright fluxes imply high isotropic luminosities of $L_{\text{iso}} \gtrsim 10^{42}$ erg s $^{-1}$. A flurry of theoretical ideas has been put forward to explain them, including: black-hole evaporation (Keane et al. 2012); magnetar hyperflares (Popov & Postnov 2013; Katz 2014); neutron-star mergers (Totani 2013; Ravi & Lasky 2014); white-dwarf mergers (Kashiyama et al. 2013); collapse of supramassive neutron stars (Falcke & Rezzolla 2014; Zhang 2014); orbiting bodies immersed in pulsar winds (Mottez & Zarka 2014); magnetar pulse-wind interactions (Lyubarsky 2014); giant pulses from magnetars near galactic centers (Pen & Connor 2015); collisions between neutron stars and asteroids (Geng & Huang 2015); giant pulses from young pulsars within supernova remnants in nearby galaxies (Connor et al. 2015) or at cosmological distances (Katz 2015); quark novae (Shand et al. 2015); and even directed signals from extraterrestrial civilizations (Luan & Goldreich 2014).

In parallel, the possibility has lingered that FRBs have a terrestrial, possibly human-made, origin (Burke-Spolaor et al. 2011; Kulkarni et al. 2014). From the start, some resemblances were noted between FRBs and “peryttons” (Burke-Spolaor et al. 2011), signals with fluxes, time structures, and roughly quadratic frequency sweeps similar to FRBs but, as opposed to FRBs, with detections in all focal-plane receivers of the telescope, indicating a

nearby source that has not been focused by the antenna dish. Petroff et al. (2015b) have recently demonstrated that peryttons arise from microwave kitchen ovens at the Parkes observatory (generally during lunchtime), when an oven door is opened while the appliance is in operation. They presented further statistical evidence that the FRBs are a truly astronomical phenomenon, distinct from the human-made peryttons.

Alternatively to these explanations for FRBs, Loeb, Shvartzvald, & Maoz (2014) proposed that FRB sources could be nearby flaring stars. Abundant types of flare stars that might provide the required FRB rates include young M-type stars, W-UMa-class stars (stable contact binaries composed of two stars of about solar mass), or other types. Flaring main-sequence stars are already known to produce coherent radio bursts with millisecond-scale durations and ~ 1 GHz flux densities of a fraction of a Jy (Lang et al. 1983; Lang & Willson 1986; Güdel et al. 1989; Bastian et al. 1990). Although details of the flare emission mechanisms are poorly understood, these bursts are thought to be produced by a cyclotron maser process, in which bunches of electrons emit coherent radio emission as they gyrate around the magnetic field of the host star (Güdel 2002; Treumann 2006; Matthews 2013). Loeb et al. (2014) argued that if FRB eruptions are produced at the bottom of the coronae of their host stars, or the eruptions cause coronal mass ejections of their own (Drake et al. 2013), the radiation will pass through a plasma blanket with a characteristic electron column density $\gtrsim 10^{10}$ cm $^{-3} \times R_{\odot} \sim 300$ cm $^{-3}$ pc, as needed to explain the observed DMs of FRBs. Such column densities are typically inferred for stellar flares (Getman et al. 2008a,b). We note that radio bursts from stellar flares are observed to be circularly polarized, like the single FRB with a polarization measurement (Petroff et al. 2015a).

To test the flare-star FRB hypothesis, Loeb et al. (2014) monitored in the optical the fields of three FRBs for variable stars. In one field, they discovered a nearby (800 pc) W UMa system at a position within the FRB radio beam. From the abundance of W UMa systems, Loeb et al. (2014) derived a probability of $\sim 5\%$ for a chance coincidence of such a system in the beam of one out of three FRB beams. However, this inference was compromised by the *a posteriori* nature of the conclusion, since the objective of specifically finding W UMa stars was not defined in advance of the search.

In this paper, we extend the observational test of the flare-star hypothesis, by means of photometric and spectroscopic monitoring and analysis of stars in 8 out of 9 known FRB fields. We find one new example of a W UMa stars in the direction of one FRB, and a periodically variable bright blue star toward another FRB. We also revisit the statistical analysis of FRB110220 and FRB140514 and conclude that they are from one and the same repeating source, rather than from two unrelated sources as claimed by Petroff et al. (2015a). The factor-of-2 decrease over 3 years in DM between the two bursts cannot arise in the intergalactic medium, invalidating any extragalactic model for FRBs in which the DM is a measure of the distance to the source. Finally, we re-assess some arguments that have been put forward against the Galactic flare-star scenario, and show

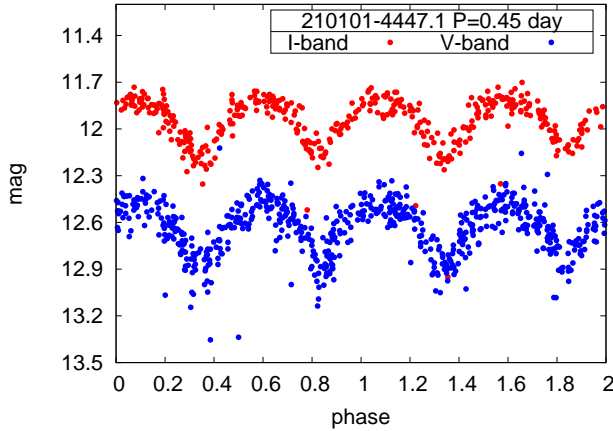


Figure 1. Phase-folded V and I light curves from ASAS for the variable star, ASAS220101-4447.1, a possible W UMa-type source for FRB110627.

that they are incorrect from a theoretical perspective, from a demonstrative observational point of view, or both.

2 OPTICAL OBSERVATIONS AND ANALYSIS OF FRB FIELDS

Following the methodology of Loeb et al. (2014) to search for bright variable stars within the radio beams of past FRBs, we have analyzed data at those locations from the All-Sky Automated Survey (ASAS) (Pojmanski 1997). ASAS uses a set of small telescopes in Chile to monitor about 3/4 of the sky to 14 mag in the optical (V and I), with data for some fields going back two decades. The ASAS catalog also permits us to find the sky density of specific types of variable stars at the Galactic longitude and latitude, (l, b) of each FRB, and thus to estimate the chance probability of finding such a star within an FRB beam.

2.1 FRB110703

In the field of this FRB, found by Thornton et al. (2013), Loeb et al. (2014) discovered, based on imaging with the Wise Observatory 1m telescope, a $V = 13.6$ mag, $V - I = 0.85$ mag, W UMa system with a period of $P = 7.84$ hr within the 14 arcmin diameter Parkes beam, 4 arcmin from the beam center. From the number (one) of W UMa's that are as bright which they found outside the beam region, and also from the known volume density of W UMa's, Loeb et al. (2014) roughly estimated a $\sim 1.7\%$ chance probability for finding such a system within the FRB beam region. ASAS data for this field confirm the V and I light-curve shapes, amplitudes, and period for this W UMa system (named ASAS233003-0248.3 in the ASAS database). Furthermore, from the ASAS catalog, we find that the actual sky density of W UMa's in the general direction of this FRB, to $V = 14$ mag, is 0.11 deg^{-2} , implying only a 0.5% random probability to find a W UMa within the 0.04 deg^{-2} Parkes beam (i.e. lower than the rough estimate, above, by Loeb et al. (2014)).

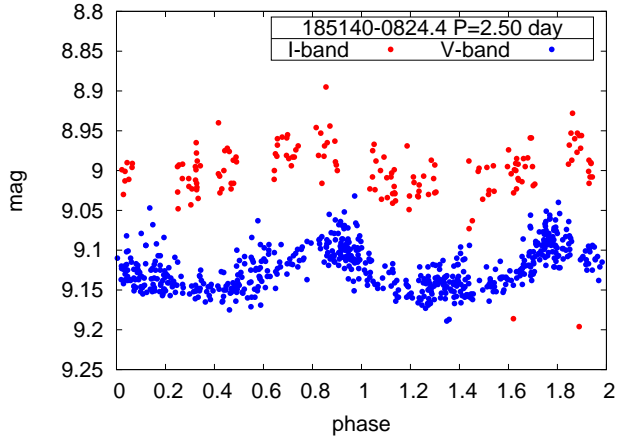


Figure 2. Phase-folded V and I light curves from ASAS for the bright variable blue star, HD174628, within the beam of FRB010621.

2.2 FRB110627

Near the position of FRB110627 (Thornton et al. 2013), we have found another bright ($V = 12.5$ mag) W UMa system, ASAS220101-4447.1. Figure 1 shows the V and I light curves, folded with a period of $P = 10.75$ hr. The period, the color ($V - I = 0.7$), and the light-curve shape (with amplitude 0.4 mag) are all characteristic of a W UMa star. The star is 29 arcmin west, i.e. about 2 beam diameters, from the center of beam No. 12 in which the FRB was detected Keane & Petroff (2015). However, beam No. 12 is on the outer ring of beams of the Parkes multi-beam receiver¹. From the technical data for FRBs at the Reasearch Data Australia Portal², the receiver orientation on the sky at the time of the observation was such that beam No. 12 was almost exactly on the western side of the outer ring (i.e. at the “3 o'clock” position). As such, the detection in this single beam could have been triggered by a side lobe of a bright FRB at the west-offset position of the W UMa. The FRB/W-UMa association is thus possible in this case. From ASAS, the W UMa sky density in this FRB's direction is 0.16 deg^{-2} . Considering that the area within which this type of side-lobe detection in beam No. 12 could have been triggered (an annular sector of opening angle 60° , centred on the receiver centre, with inner radius 65 arcmin and outer radius 80 arcmin, i.e. at the location of the W UMa star) is about 0.3 deg^2 , the chance probability for the presence of a W UMa there is about 5%.

2.3 FRB010621

In the field of this FRB discovered by (Keane et al. 2012), ASAS data (Pojmanski & Maciejewski 2005, Fig. 2, see) show that the bright blue star ($V = 9.1$ mag, $V - I = 0.1$), HD174628, 6.7 arcmin from the reported FRB radio beam center, is variable with a period of 2.5 days and a V -band amplitude of ~ 0.07 mag. Figure 3 shows the star's spectrum (see below) with its best-fitting model template, a

¹ see e.g., <http://www.atnf.csiro.au/research/multibeam/instrument/descripti>

² <http://http://supercomputing.swin.edu.au/data-sharing-cluster/parkes-fr>

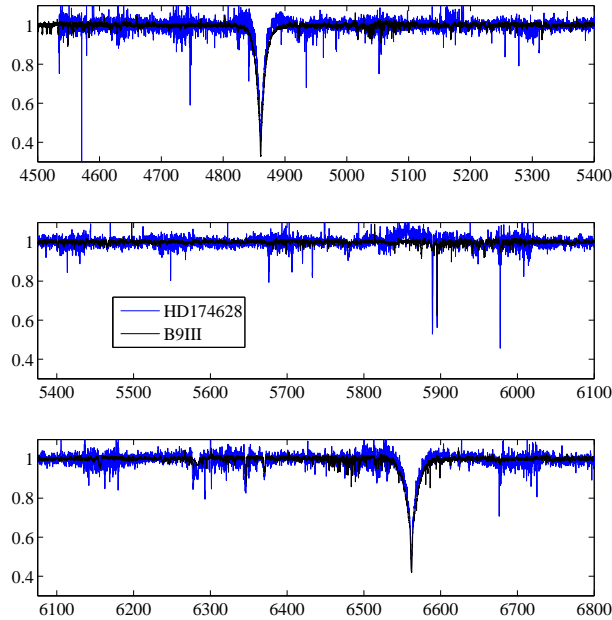


Figure 3. Continuum-normalized Wise eShel spectrum of the periodic variable HD174628, with its best-fitting model stellar template, a B9 III star. H α and H β are the prominent lines.

B9 III giant with effective temperature $T \sim 11,000\text{K}$, surface gravity $\log g = 3.5 \pm 0.5$, and projected rotational broadening $V_{\text{rot}} \sin i = 70 \pm 10 \text{ km s}^{-1}$. The spectral type, period, and rotational broadening are all characteristic of a class of non-radially pulsating stars called slowly pulsating B-stars (SPBs; e.g. De Cat 2007). HD174628 is somewhat unusual, however, in that SPBs typically have pulse amplitudes of only 0.01, and 0.025 at most.

To test for radial-velocity variations, or for the possibility that the photometric variations are caused by some other star along the line of sight, whether or not physically associated with the B star, we obtained high-resolution spectra at 8 separate epochs, as follows. Spectra with resolution $R \approx 10,000$ were obtained using the Wise Observatory 1m telescope with the eShel high resolution fiber-fed echelle spectrograph on four nights over a 32-day period, as detailed in Table 1. A one-hour exposure was taken each night. A month later, the Levy echelle spectrometer on the Automated Planet Finder (Vogt et al. 2014, APF;) 2.4m telescope at Lick Observatory was used to further obtain $R \approx 100,000$ spectra at three epochs over 100 days. Each epoch consisted of four consecutive 15-min exposures that were analyzed individually. Both data sets were reduced and calibrated using standard procedures.

We have processed each individual spectrum through the TODCOR two-dimensional correlation program (Zucker & Mazeh 1994), attempting to fit each epoch with two stellar templates with variable radial velocities (RVs). In no cases do we find evidence of a secondary, late-type stellar component in the spectra. The spectral features in the spectrum consist of only a handful of broad absorption lines, and therefore the RV precision is not much better

than c/R . In the Wise data, we estimate a single-epoch RV precision of $\sim 4 \text{ km s}^{-1}$. In the Lick-APF spectra, from the scatter in RV among each set of four individual exposures taken over an hour, we estimate the RV precision at $\sim 1 \text{ km s}^{-1}$. As listed in Table 1, on all but one of the 8 nights that the star was observed, the RV is consistent with a constant barycenter-corrected value of $\approx -16 \text{ km s}^{-1}$. One APF epoch shows a formally significant deviation to an RV of $\approx -22 \text{ km s}^{-1}$, but given the consistent velocities at all other epochs, at various phases of the 2.5 day photometric period, we suspect this single deviant point is a fluke. We detect also no significant differences in $V_{\text{rot}} \sin i$ among epochs.

We have thus found no explanation for the 7%-level, few-day-period photometric modulation of this star, other than it being an SPB star with an unusually high amplitude. A variable line-of sight late-type star responsible for the variations would have contributed at least 10% of the B-star flux, which would have been detected in the spectrum and can thus be ruled out. A contact binary composed, e.g., of two $10M_{\odot}$ B-type giants with a separation of $25R_{\odot}$ would have an orbital period of 3.3 days. If viewed nearly pole-on to the orbital plane, the photometric variability at the $\pm 5\%$ level could be due to ellipsoidal tidal distortion of the components. However, to satisfy the constraint of RV variations with amplitude $K < 2 \text{ km s}^{-1}$, despite the 200 km s^{-1} orbital velocity, the system would need to be within 0.5 degree of pole-on. Furthermore, one would then expect the synchronized projected rotation velocity to be equally small, rather than the observed $v \sin i = 70 \pm 10 \text{ km s}^{-1}$. The same problems would arise, but would be less severe, if the binary companion in the low-inclination orbit were a roughly solar-mass object—a main-sequence star, white dwarf, neutron star or black hole. For periods of 3.3 days, the B-star’s orbital velocity would be of order $30\text{--}40 \text{ km s}^{-1}$, and thus an inclination within 5 degrees of pole-on would be required, in order to satisfy the observed $\Delta RV \lesssim 4 \text{ km s}^{-1}$ limits. About one-half of SPB stars are magnetic, with fields of order hundreds of Gauss and sometimes close to $\sim 1 \text{ kG}$ (Hubrig et al. 2009), not unlike the $\sim 1 \text{ kG}$ fields of low-mass flare stars. B stars are relatively rare, and more so SPB stars. For example, in the 105 deg^2 *Kepler* field, there are only about 10 B stars brighter than 9 mag, and only 4 of them are SPBs (all with amplitudes 1-3 orders of magnitude smaller than HD174628). A density of $< 0.04 \text{ deg}^{-2}$ (McNamara et al. 2012), can thus serve as a firm upper limit for SPBs with the large HD174628 pulsation amplitude. The presence of this unusual star in the 0.042 deg^2 Parkes beam in one out of 8 FRB fields studied (random probability $< 1.4\%$) is therefore intriguing. However, again, care must be taken with such *a posteriori* statistical conclusions, and therefore we cannot claim a secure association between the star and the FRB.

We note again that, for this FRB, Bannister & Madsen (2014) have used velocity-resolved observations of H α and H β Balmer line emission from diffuse ionized gas in the FRB direction, combined with a Galactic rotation model, to obtain the emission measure of the Milky Way ionized gas column along the line of sight. From the emission measure, they estimated the Galactic electron column density. They concluded that the DM of the FRB, if all due to the Galactic interstellar medium, places the FRB source within our Galaxy, at a distance of 8-20 kpc. The B star HD174628,

discussed above, is at a distance of $0.4 - 1$ kpc, depending on its exact spectral class and the line-of-sight extinction that it undergoes.

2.4 Non-detections

Apart from the above three FRB fields, we have searched another five FRB fields for bright short-period ($\lesssim 1$ day) variable stars, but have not found any, as follows. The fields of FRB110220 and FRB120127 were already monitored and reported by Loeb et al. (2014), who found no short-period stars brighter than 16 mag. This null result is confirmed by the shallower but longer-term ASAS data for these two fields, as well as for FRB011025 (Burke-Spolaor & Bannister 2014). Near the position of FRB131104 (Ravi et al. 2015), ASAS data reveal a W UMa with $V = 13.5$, $V - I = 1$, and a period of $P = 7.6$ hr. However, the star is 28 arcmin south of the center of beam No. 5 in which the FRB was detected. Given the receiver orientation at the time (Ravi et al. 2015), an FRB from the W UMa position would have triggered beam No. 12, rather than No. 5. This W UMa star is therefore not the source of this FRB.

FRB010824, the first (Lorimer et al. 2007) FRB discovered, adjacent to the Small Magellanic Cloud (SMC), and at 30 Jy still the brightest one known, is also the only one detected in more than one focal-plane beam of the Parkes multi-beam receiver. The three beams with detections permit a more precise localization of the FRB (see Kulkarni et al. (2014), and also Keane & Petroff (2015), who report a weak detection even in a fourth beam), to a roughly rectangular region about 9 arcmin by 1 arcmin in size. ASAS data for this area again reveal no candidate short-period optical variables to 14 mag. This SMC field has also been monitored for four years by the Optical Gravitational Lensing Experiment (OGLE-IV) using the 1.3 m Warsaw University telescope in Chile (Udalski et al. 2015). Within the FRB error region, we find no short-period variable stars in OGLE-IV to $V = 18.5$ mag. From the OGLE-IV data in the SMC region (Pawlak et al. 2013), we have counted the number of periodic variables redder than $V - I = 0.5$ with periods less than 1 day, to $V = 18.5$ mag, and find a density of 0.5 deg^{-2} . These variables should include all main-sequence contact binaries, including W UMa types. Despite the color cut, this estimate might be contaminated by reddened main-sequence B-type contact binaries in the SMC itself, and therefore the density is a conservative upper limit. The product of the density and the error area gives a chance probability of 0.13% of finding a W UMa within the error region.

The field of FRB121102, discovered by Spitler et al. (2014) with Arecibo, is north of the $+28^\circ$ declination limit of ASAS, and in the mid-plane of the Galaxy (latitude $b = -0.2^\circ$), where crowding and extinction make the type of optical followup described here difficult.

2.5 Association probability of FRBs and W UMa's

Table 2 summarises some of the parameters of the ten known FRBs and the candidate stellar counterparts that we have found for some of them. In view of the above results, we revisit the question of the probability that FRBs and W UMa's

are associated. In 8 FRB fields that we have searched, we have found one or two possible associations with a W UMa system, as follows. Within the beam of FRB110703, there is the W UMa system discovered by Loeb et al. (2014), with a 0.5% random probability for such a system within the FRB beam. However, as already mentioned, to avoid a *posteriori* statistics, this field and this system perhaps should not be counted. In FRB110627, there is a W UMa separated by 29 arcmin from the FRB beam center, but a side-lobe detection of a source at that position is a real possibility, given the receiver orientation at the time, with a 5% estimated chance probability for a W UMa. Apart from these two W UMa stars, in the field of FRB010621 we have found a likely SPB pulsator. We have not been able to show that it is connected to variability in a low-mass star, and it is unclear whether or not the SPB star itself is related to the FRB. We will therefore not consider it further in the accounting below.

As seen in Table 1, five of the eight FRB fields have an *a priori* random probability of 0.5 to 0.8% of hosting a W UMa system, two fields have a probability of 4–5%, and one field (the SMC field, which is well localized) has a low probability of 0.13%. To estimate the random probability of the experimental result, we find the binomial probabilities of the observed number of successes, or more, in each of the three sets of fields with similar probabilities (for the 0.5–0.8% fields we conservatively assume 0.8%). We then multiply the three binomial probabilities. The associations between FRBs and variable stars may exist in: zero out of 7 cases (if we do not count the first case, of FRB110703, and none of the other associations is real); in 1 of 7 cases (if the FRB110628 association is correct, and then the random binomial probability is 9%); or 2 of 8 cases (if we do count the case of FRB110703, in which case the random probability of the experimental result is 3.6%). Finally, if our accounting includes all types of bright short-period variable and potentially flaring stars, so that we include also the SPB star HD174628 in the field of FRB010621, then the chance probability for the experimental result is $(1.33 - 5) \times 10^{-3}$. Given this range, we cannot yet claim to have established an association between the two phenomena. In any case, the fact that bright W UMa stars, or bright flaring stars of any type, were *not* found in most of the fields, does not rule out the flare-star/FRB connection hypothesis. Stellar sources of FRBs will likely have a distribution of optical luminosities and fluxes, possibly uncorrelated with the FRB luminosities, and therefore any flux-limited survey like ours for the optical counterparts will uncover only a fraction of the associations.

3 FRB110220 AND FRB140514 ARE FROM THE SAME REPEATING SOURCE

Petroff et al. (2015a) re-monitored the sites of a number of FRBs with the Parkes Radio Telescope for a total of 85 hours on sky, leading to the real-time discovery of FRB140514 at the position of the previous FRB110220. Although only about 21 hours out of the 85 hours were spent on the field of FRB110220, all 85 hours were spent on *some* previous FRB location, and could have led to the discovery of a new FRB at the location of a previous one. Therefore for the purpose of calculating the chance probability of detecting an

Table 1. HD174628 spectral observations and radial velocities

UT Date	UT Time	JD −2456700	Observ.	RV [km s ^{−1}]
2014.05.14	01:12	91.55	Wise	-14.4 ± 3.4
2014.06.10	23:02	119.46		-17.5 ± 2.7
2014.06.12	00:58	120.54		-14.0 ± 4.0
2014.06.14	00:43	122.53		-8.3 ± 4.3
2014.06.14	21:07	123.38	Lick	-12.5 ± 3.9
2014.07.10	06:43	148.78		-21.5 ± 1.1
2014.10.14	02:53	244.62		-15.3 ± 1.0
2014.10.18	03:07	248.63		-16.8 ± 0.9

Table 2. FRBs, candidate counterparts, and random probabilities for W UMa

Date (1)	l (2)	b (3)	Ref. (4)	RA(J2000) (5)	DEC (6)	Counterpart RA(J2000) (7)	DEC (8)	Σ deg ^{−2} (9)	Prob % (10)	Comments (11)
010621	25	−04	Keane et al. (2012)	18 52	−08 29	18 51 40	−08 24.4	0.16	4.4	B giant, $V = 9.1$ mag, beam 10
010824	301	−42	Lorimer et al. (2007)	01 18 06	−75 12 19	...	...	0.50*	0.13	...
011025	357	−20	Burke-Spolaor & Bannister (2014)	09 07	−40 37	...	...	0.19	0.8	...
110220	51	−55	Thornton et al. (2013)	22 34	−12 24	...	...	0.10	0.5	...
110627	356	−42	Thornton et al. (2013)	21 03 44	−44 44 19	21 01 01	−44 47.0	0.16	5.0	W UMa, $V = 12.4$ mag, beam 12
110703	81	−59	Thornton et al. (2013)	23 30	−02 52	23 30 03	−02 48.3	0.10	0.5	W UMa, $V = 13.5$ mag
120127	49	−66	Thornton et al. (2013)	23 15	−18 25	...	...	0.11	0.5	...
121102	175	−0	Spitler et al. (2014)	05 32 10	33 05 13	not	searched	0.15	—	Arecibo FRB, Galactic plane
131104	261	−22	Ravi et al. (2015)	06 44 10	−51 16 40	...	...	0.18	0.8	...
140514	51	−55	Petroff et al. (2015a)	22 34 06	−12 18 47	...	...	—	—	Site of FRB110220

Notes.- (2)(3)–Galactic longitude and latitude; (7)(8) coordinates of candidate stellar counterpart; (9) sky density, to $V = 14$ mag, of W UMa stars; (10) Probability of finding a W UMa within the FRB beam area. * density of W UMa’s to $V = 18.5$ mag, in the SMC field.

unrelated FRB within a re-monitored FRB region, we must consider all 85 hours of on-sky time. Petroff et al. (2015a) estimated this chance probability at a high level of 32%, and concluded that the two bursts are from different sources. However, based on the available information and our own simple and straightforward calculation, we contest this conclusion, as detailed below.

According to Petroff et al. (2015a), the field of FRB110220 was observed with a cycle of five telescope pointings, called a “gridding” pattern (Morris et al. 2002). In the first pointing the central, 14-arcmin-diameter, beam of the receiver was pointed at the same position as the center of the beam in which FRB110220 was detected. In the subsequent four pointings, the telescope was pointed 9 arcmin north, south, east, and west of the first pointing, and then the cycle was repeated. The real-time FRB140514 was detected only in the central beam of one of those 9-arcmin north-offset pointings. (Actually, from comparison of the published coordinates, it appears the offset was only about 5 arcmin north of the FRB110220 coordinates in Thornton et al. (2013).) At any given moment in the real-time survey, the central beam was the only one covering part or all of the beam area of the original burst. Thus, for the purpose of estimating the chance probability of an unrelated burst occurring as close to the location of the original burst as was, in fact, observed for the real-time burst, the monitored solid angle that needs to be considered is just the solid angle covered by the central beam. This solid angle is $\pi(7/60)^2 \text{ deg}^2 = 0.042 \text{ deg}^2$. For

an assumed all-sky FRB rate of 3300 day^{-1} (Rane et al. 2015), and the 85 hr on-sky time of the Petroff et al. (2015a) survey, one then expects 0.0125 of an event within the central beam. However proper account must also be taken of the fact that, during the entire survey, an FRB was *not* detected in any of the other 12 beams of the receiver, within which we would have expected 0.15 of an event outside the central beam, with a complementary probability for non-detection of 0.85. The probability for an unrelated FRB being detected in the central beam of the real-time experiment, and only there, is therefore $0.0125 \times 0.85 = 1\%$. Conversely, we can state with 99% confidence that the original FRB and the real-time FRB are from the same, repeating, source. We note that, if we use the somewhat lower FRB rate estimates, 2500 day^{-1} Keane & Petroff (2015); Macquart & Johnston (2015) or 2000 day^{-1} (Burke-Spolaor & Bannister 2014), the chance probability will go down correspondingly and the confidence of our conclusion rises further.

The DMs of the original and the real-time FRBs were 945 and 562 pc cm^{−3}, respectively, i.e. a difference of almost a factor of 2. If, as we have argued, the two FRBs are from the same source, such a change in the intervening intergalactic free electron column density over the course of about 3 years is impossible. This then rules out intergalactic dispersion as the origin of the large DMs of FRBs. Conversely, in the flare-star scenario, there is no particular reason why the plasma blanket around a flare star would not change between bursts separated by years. Such changes are even to

be expected, given that the coronal plasma should be out-flowing, as argued by Loeb et al. (2014). A repeating FRB in the same beam with changing DM could still arise in an extragalactic scenario, but only if the DM is produced by electrons local to the source (e.g. Connor et al. (2015)). The source could be a true repeating one (i.e. the source is not destroyed in a burst), or there could be several separate FRB sources in an “FRB-active” galaxy, or cluster of galaxies.

4 THEORETICAL CONSIDERATIONS REGARDING THE FLARE-STAR MODEL

We now address a number of arguments that have been raised against the flare-star hypothesis of FRBs. One claim has been that the coronal plasma blanket around a flaring star would necessarily be too dense to produce the observed strict f^{-2} frequency dependence of the pulse arrival times of FRBs (Dennison 2014; Tuntsov 2014). For the f^{-2} behavior, a density $n_e < 10^9 \text{ cm}^{-3}$ is required since the plasma frequency is $\nu_p = (\omega_p/2\pi) = 0.9 \text{ GHz}(n_e/10^{10} \text{ cm}^{-3})^{1/2}$ (Rybicki & Lightman 1986). However, for example, Getman et al. (2008a,b) have found that for the brightest X-ray flares from pre-main-sequence stars, the coronas have electron column densities in the range $N_e = 10^{21-22} \text{ cm}^{-2}$ (as implied by the DMs of FRBs) but also length scales as high as $R \sim 10^{12-13} \text{ cm}$, indicating mean densities of $n_e \sim 10^{8-9} \text{ cm}^{-3}$. As such, one would expect to see the f^{-2} frequency sweep in stellar radio flares. Indeed, there are such examples. Osten & Bastian (2008) show high-time-resolution radio data for the active young M-star AD Leonis, with a clear delay in signal arrival time with decreasing frequency. The typical drift rates are 2 GHz s^{-1} . Although, in this specific star, the observed drift rate is an order of magnitude larger than seen in FRBs, and it is hard to say what is the exact frequency dependence of the sweep, it shows that known stellar flares do sweep in radio frequency, at least roughly in the required sense. We encourage radio observers of stellar flares to obtain more such high-time-resolution data of more stars, to broaden the known phenomenology of these effects.

Another argument against a stellar-flare origin for FRBs has been that radio emission would be suppressed through free-free absorption in the corona that produced its DM if the corona is limited by the radius of the star, R_* , and its temperature is limited by the virial temperature of the star, $\sim 10^7 \text{ K}$ (Luan & Goldreich 2014). However, the optical depth for free-free absorption at a frequency of 1.4 GHz declines with increasing temperature T and size R of the emitting region as (Kulkarni et al. 2014),

$$\tau_{\text{ff}} = 0.1 \left(\frac{T}{10^8 \text{ K}} \right)^{-3/2} \left(\frac{R}{10^{13} \text{ cm}} \right)^{-1} \left(\frac{DM}{10^3 \text{ cm}^{-3} \text{ pc}} \right)^2, \quad (1)$$

and becomes negligible for the observed DMs of FRBs at $T > 10^8 \text{ K}$ and $R \gg 10R_*$. Observationally, Getman et al. (2008a) and Getman et al. (2008b) show that pre-main-sequence flare stars often have flares with temperatures $T \sim 10^{8-9} \text{ K}$ over a spatial scale $R \sim 10^2 R_* \sim 10^{13} \text{ cm}$, invalidating the argument for significant free-free absorption. The free-free optical depth scales with frequency as ν^{-2} , and therefore for the above parameters of real stellar flares, we

would not expect to detect FRBs at frequencies much lower than 1.4 GHz . This is consistent with a recent strong limit on FRB detection at 145 MHz obtained by Karastergiou et al. (2015) using the LOFAR array, and requiring that FRBs have a rising flux density spectrum between these two frequencies.

Kulkarni et al. (2014) have argued that radio emission from flare stars would necessarily be accompanied by bright X-ray flares. Considering the rate of FRBs and comparing it to the known statistics of all-sky X-ray variability, they concluded that there is a shortage of known X-ray flares, and hence FRBs cannot originate from flaring stars. Flaring stars indeed erupt in both radio and X-ray wavelengths. There is a well-known correlation, over many orders of magnitude in luminosity, between the radio and X-ray luminosities of flares from stars with active coronae, whether between the peak luminosities or the time-averaged luminosities (e.g. Benz et al. 1994). However, there is no one-to-one correspondence between individual radio and X-ray flares, as would be required in order to derive an expected rate of X-ray flares from the observed FRB rate. For example, Williams et al. (2015) have monitored a close M-star binary simultaneously in many bands, including radio and X-rays, and report a general lack of correlation between flares in any two bands.

Thus, none of the above arguments against the flare-star origin of FRBs is valid, mainly because the observed properties of some stellar flares already show that radio flares with characteristics similar to FRBs are possible. A recent addition to this list of similarities is the high circular polarization measured in FRB140514 (Petroff et al. 2015a); radio bursts from flaring stars are often 100% circularly polarized.

Most recently, Katz (2015) showed that the non-monotonic dependence of burst widths on dispersion measure excludes the intergalactic medium as the location of scattering that broadens the FRBs in time. This argues in favor of a local origin for FRBs, where the observed DM is intrinsic to the FRB sources, as expected in the case of flaring Galactic stars.

5 CONCLUSIONS

The ten published detections of FRBs have triggered a wealth of proposed interpretations, ranging from exotic processes at cosmological distances to atmospheric and terrestrial sources. Loeb et al. (2014) have previously suggested that FRB sources could be nearby flare stars, and pointed out the presence of a W-UMa-type contact binary within the beam of one out of three FRB fields that they examined. Using time-domain optical photometry and spectroscopy, we now find a possible W UMa counterpart to another FRB, and a rare slow-pulsating B star in the beam of a third FRB. The random probabilities for having one or two real W UMa’s within the eight studied FRB beam areas are $\sim 9\%$ and 4% , respectively.

Contrary to previous claims, we conclude with 99% confidence that two FRBs which were discovered 3 years apart within the same radio beam are from the same repeating source. The different DMs of the two bursts then rule out a cosmological origin for the DMs, but are consistent with the flare-star scenario with a varying plasma blanket

between bursts. Finally, we have shown that the theoretical objections that were raised against a Galactic origin of FRBs are incorrect because they are circumvented by the observed properties of some stellar radio flares (Getman et al. 2008a,b). We conclude that the flare-star-origin hypothesis for FRBs is still a strong player in the game, and is consistent with all current observations. In contrast, the idea that the intergalactic medium is responsible for the DM of FRB sources is in direct contradiction to the observation of a changing DM between two FRBs that, as we have argued, are almost certainly from the same repeating source.

ACKNOWLEDGMENTS

We thank E. Ofek for his input regarding the localisation of the Lorimer burst, J. Miralda-Escude for comments, W. Freedman and B. Madore for data obtained at the Magellan Telescopes, and the anonymous referee for very useful suggestions. A.L. acknowledges support from the Sackler Professorship by Special Appointment at Tel Aviv University. This work was supported in part by NSF grant AST-1312034 (A.L.) and Grant 1829/12 of the I-CORE program of the PBC and the Israel Science Foundation (D.M. and T.M.). The research by T.M. leading to these results has received funding from the European Research Council under the EU's Seventh Framework Programme (FP7/(2007-2013)/ERC Grant Agreement No. 291352), and Israel Science Foundation grant No. 1423/11 to T.M. Research by Y.S. is supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Oak Ridge Associated Universities through a contract with NASA. R.M.R. acknowledges support from NSF grant AST-1413755. Research at Lick Observatory is supported by the University of California and partially supported by a generous gift from Google. M.K. acknowledges support by the Polish National Science Center under grant DEC-2011/03/B/ST9/03299.

REFERENCES

- Albrow, M.D., et al. 2009, *MNRAS*, 397, 2099
- Bannister, K. W., & Madsen, G. J. 2014, *MNRAS*, 440, 353
- Bastian, T. S., Bookbinder, J., Dulk, G. A., & Davis, M. 1990, *ApJ*, 353, 265
- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, *Reviews of Modern Physics*, 56, 255
- Benz, A. O., Kosugi, T., Aschwanden, M. J., et al. 1994, *Sol. Phys.*, 153, 33
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Bianchi, L., et al. 2007, *ApJS*, 173, 659
- Burke-Spolaor, S., Bailes, M., Ekers, R., Macquart, J.-P., & Crawford, F., III 2011, *ApJ*, 727, 18
- Burke-Spolaor, S., & Bannister, K. W. 2014, *ApJ*, 792, 19
- De Cat, P. 2007, *Communications in Asteroseismology*, 150, 167
- Connor, L., Sievers, J., & Pen, U.-L. 2015, *arXiv:1505.05535*
- Dennison, B. 2014, *MNRAS*, 443, L11
- Drake, J. J., Cohen, O., Yashiro, S., & Gopalswamy, N. 2013, *ApJ*, 764, 170
- Ducati, J.R., Vevillacqua, C.M., Rembold, S.B., & Ribeiro, D. 2001, *ApJ*, 558, 309
- Eker, Z., Demircan, O., & Bilir, S. 2008, *MNRAS*, 386, 1756
- Falcke, H., & Rezzolla, L. 2014, *A&A*, 562, A137
- Geng, J. J., & Huang, Y. F. 2015, *arXiv:1502.05171*
- Getman, K. V., Feigelson, E. D., Broos, P. S., Micela, G., & Garmire, G. P. 2008, *ApJ*, 688, 418
- Getman, K. V., Feigelson, E. D., Micela, G., et al. 2008, *ApJ*, 688, 437
- Güdel, M., Benz, A. O., Bastian, T. S., et al. 1989, *A&A*, 220, L5
- Güdel, M. 2002, *ARA&A*, 40, 217
- Hubrig, S., Briquet, M., De Cat, P., et al. 2009, *Astronomische Nachrichten*, 330, 317
- Karastergiou, A., et al. 2015, *arXiv:1506.03370*
- Kashiyama, K., Ioka, K., & Meszaros, P. 2013, *ApJ*, 776, L39
- Katz, J. I. 2014, *Phys. Rev. D*, 89, 103009
- Katz, J. I. 2015, *arXiv:1505.06220*
- Keane, E. F., Stappers, B. W., Kramer, M., & Lyne, A. G. 2012, *MNRAS*, 425, L71
- Keane, E. F., & Petroff, E. 2015, *MNRAS*, 447, 2852
- Kulkarni, S. R., Ofek, E. O., Neill, J. D., Zheng, Z., & Juric, M. 2014, *ApJ*, 797, 70
- Lang, K. R., Bookbinder, J., Golub, L., & Davis, M. M. 1983, *ApJ*, 272, L15
- Lang, K. R., & Willson, R. F. 1986, *ApJ*, 305, 363
- Loeb, A., Shvartzvald, Y., & Maoz, D. 2014, *MNRAS*, 439, L46
- Loeb, A., Shvartzvald, Y., & Maoz, D. 2014, *MNRAS*, 439, L46
- Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, *Science*, 318, 777
- Lorimer, D. R., Karastergiou, A., McLaughlin, M. A., & Johnston, S. 2013, *arXiv:1307.1200*
- Luan, J., & Goldreich, P. 2014, *ApJ*, 785, L26
- Lyubarsky, Y. 2014, *MNRAS*, 442, L9
- Macquart, J.-P., & Koay, J. Y. 2013, *ApJ*, 776, 125
- Macquart, J.-P., & Johnston, S. 2015, *arXiv:1505.05893*
- Matthews, L. D. 2013, *PASP*, 125, 313
- McGale, P.A., Pye, J.P., & Hodgkin, S.T. 1996, *MNRAS*, 280, 627
- McNamara, B. J., Jackiewicz, J., & McKeever, J. 2012, *AJ*, 143, 101
- Mészáros, P. 2013, *Astroparticle Physics*, 43, 134
- Molnar, L.A., Van Noord, D.M., & Steenwyk, S.D. 2013, *arXiv:1310.0539*
- Morris, D. J., Hobbs, G., Lyne, A. G., et al. 2002, *MNRAS*, 335, 275
- Mottez, F., & Zarka, P. 2014, *A&A*, 569, A86
- Osten, R. A., & Bastian, T. S. 2008, *ApJ*, 674, 1078
- Pawlak, M., Graczyk, D., Soszyński, I., et al. 2013, *Acta Astronomica*, 63, 323
- Pen, U.-L., & Connor, L. 2015, *arXiv:1501.01341*
- Petroff, E., Bailes, M., Barr, E. D., et al. 2015a, *MNRAS*, 447, 246
- Petroff, E., Keane, E. F., Barr, E. D., et al. 2015b, *arXiv:1504.02165*
- Pickles, A. J. 1985, *ApJS*, 59, 33

- Pickles, A. J. 1998, *PASP*, 110, 863
- Piran, T. 2004, *Reviews of Modern Physics*, 76, 1143
- Pojmanski, G. 1997, *Acta Astronomica*, 47, 467
- Pojmanski, G., & Maciejewski, G. 2005, *Acta Astronomica*, 55, 97
- Popov, S. B., & Postnov, K. A. 2013, *arXiv:1307.4924*
- Prugniel, P., & Soubiran, C. 2001, *A&A*, 369, 1048
- Rane, A., Lorimer, D. R., Bates, S. D., et al. 2015, *arXiv:1505.00834*
- Ravi, V., & Lasky, P. D. 2014, *MNRAS*, 441, 2433
- Ravi, V., Shannon, R. M., & Jameson, A. 2015, *ApJ*, 799, L5
- Rucinski, S. M. 1997, *AJ*, 113, 407
- Rybicki, G. B., & Lightman, A. P. 1979, *Radiative Processes in Astrophysics*, 1986, Ch. 6.
- Shand, Z., Ouyed, A., Koning, N., & Ouyed, R. 2015, *arXiv:1505.08147*
- Spitler, L. G., Cordes, J. M., Hessels, J. W. T., et al. 2014, *ApJ*, 790, 101
- Thornton, D., Stappers, B., Bailes, M., et al. 2013, *Science*, 341, 53
- Totani, T. 2013, *PASJ*, 65, L12
- Treumann, R. A. 2006, *A&A Rev.*, 13, 229
- Trott, C.M., Tingay, S.J., & Wayth, R.B. 2013, *ApJ*, 776, L16
- Tuntsov, A. V. 2014, *MNRAS*, 441, L26
- Udalski, A., Szymański, M. K., & Szymański, G. 2015, *Acta Astronomica*, 65, 1
- Vogt, S. S., Radovan, M., Kibrick, R., et al. 2014, *PASP*, 126, 359
- Waxman, E., & Loeb, A. 1999, *ApJ*, 515, 721
- Williams, P. K. G., Berger, E., Irwin, J., Berta-Thompson, Z. K., & Charbonneau, D. 2015, *ApJ*, 799, 192
- Yildiz, M., & Doğan, T. 2013, *MNRAS*, 430, 2029
- Zhang, B. 2014, *ApJ*, 780, L21
- Zucker, S., & Mazeh, T. 1994, *ApJ*, 420, 806